Report from Dagstuhl Seminar 14082

Visualization and Processing of Higher Order Descriptors for Multi-Valued Data

Edited by

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Abstract

This report documents the program and the outcomes of Dagstuhl Seminar 14082 "Visualization and Processing of Higher Order Descriptors for Multi-Valued Data". The seminar gathered 26 senior and younger researchers from various countries in the unique atmosphere offered by Schloss Dagstuhl. The focus of the seminar was to discuss modern and emerging methods for analysis and visualization of tensor and higher order descriptors from medical imaging and engineering applications. Abstracts of the talks are collected in this report.

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Edited in cooperation with Tom Dela Haije

1 Executive Summary

Ingrid Hotz
Anna Vilanova Bartroli

Higher Order Descriptors for Multi-Valued Data

This seminar is the 5th in a series of Dagstuhl Seminars devoted to the visualization and processing of higher-order descriptors, of which tensors are a special case. They provide a natural language to describe phenomena in physics or image processing, e.g. medical imaging, fluid dynamics, or structural mechanics. Due to the increasing complexity of data generated in the engineering industry and the rapid advances in medical imaging, multi-valued data have gained significant importance in scientific visualization and image processing. Compared to their importance analysis and processing tools are still relatively rare.

In many scientific and engineering applications, as modern product development processes, simulations are an essential part of the advancement of the field. The results are large and complex data sets often comprising multi-filed data of various kind. Thereby, the tensor concept is essential for the description of physical phenomena related to anisotropic behavior.

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Examples for second-order tensors are stress and strain fields, inertia tensors, and orientation distribution tensors. Higher-order tensors occur when multiple vector fields or second-order tensors are set into relation, e.g., the stiffness tensor relating stress and strain. The field of engineering faces many open problems in tensor field analysis and visualization.

In medical imaging, multi-valued data include diffusion-weighted magnetic resonance imaging (dMRI), a medical imaging modality that allows the measurement of water diffusion in tissue (e.g., white matter or muscle) in vivo. Simple models approximate the diffusion in fibrous tissue by a second-order diffusion tensor (i.e., a positive semi-definite 3×3 matrix). But, often the acquired data is more complex and cannot be sufficiently described by the second-order tensor model and requires higher-order descriptors (i.e., higher-order tensors or spherical harmonics).

Even though these applications are very different in their nature they face many shared challenges associated with this highly complex data, which can profit from a multidisciplinary approach. The idea of this Dagstuhl Seminar was to bring together key researchers for disciplines ranging from visualization and image processing to applications in structural mechanics, fluid dynamics, and numerical mathematics.

Seminar Topics and Breakout Sessions

The seminar has been organized in presentation and breakout sessions. The presentation sessions gave the participants the possibility to presented recent developments in the multidisciplinary field. The talks covered a broad variety of topics related to both theoretical and practical issues. They served as basis for inspiring discussions across the application areas, which demonstrated that there are many shared issues related to analyzing and visualizing fields of tensors and higher-order descriptors. Besides the presentations, we put an emphasis on breakout sessions, which were very successful already in the previous meeting. They were targeted at fostering focused discussions in smaller groups. During a first session the group defined some driving objectives that partially already emerged in preparatory discussions:

- Statistics on higher-order descriptors and visualization of uncertainty
- Generalization of mathematical framework to higher-order descriptors
- Features on tensor visualization
- Next generation diffusion MRI

Most issues identified in the call have been discussed. Subjects that found special attention can be summarized as: Fundamental general topics, as tensor interpolation, statistics, morphology, and topology; Questions related to pattern description and detection; More specific issues like the analysis of ensembles, the visualization and measurement of differences and anomalies for engineering as well as for medical data sets. Further, there has been much interest in double pulse field gradient methods that have been discussed as possible next generation diffusion MRI. The outcome of the sessions can also be seen at http://www.dagstuhl.de/wiki/index.php/14082#Breakout_topics

The breakout sessions again turned out to be very successful. The format of the breakout sessions fits very well in the Dagstuhl environment promoting discussions and interactions. We could also observe that, for some topics, it is not easy to go beyond a list of challenges in such a short time frame. This motivates to strengthen these sessions by pre-defining topics in preparation of the meeting and asking selected participants for related statements.

Outcomes

The participants all agreed that the meeting was successful and stimulating. Seminar participants are already collaborating on a Springer book summarizing the results of the meeting. The Springer book will have about seventeen chapters authored by the meeting participants. It is also planned to summarize the results of two breakout sessions as a chapter of the book. The participants Thomas Schultz and Ingrid Hotz agreed on taking the lead for the collection of the contributions and the assembly of the book. We expect the book to be published in 2015.

It was voted that the group will apply for another meeting in this series, and that in addition to the current organizer (Ingrid Hotz) there will be two new organizers (Thomas Schultz, University Bonn Germany and Evren Özarslan, Harvard Medical School – Boston, US) for the next event.

Acknowledgement

The organizers thank all the attendees for their contributions and extend special thanks to the team of Schloss Dagstuhl for helping to make this seminar a success. As always, we enjoyed the warm atmosphere of the Schloss, which supports both formal presentations as well as informal exchanges of ideas.

2 Table of Contents

3 Overview of Talks

3.1 Morphology for Color Images by Means of Loewner Order and Einstein-Addition for Matrix Fields

Bernhard Burgeth (Universität des Saarlandes, DE)

Joint work of Burgeth, Bernhard; Kleefeld, Andreas

In this talk we present an approach to (elementary) morphology for colour images that relies on the existing order based morphology for matrix fields of symmetric 2×2-matrices. An RGB-image is embedded into a field of those 2×2-matrices by exploiting the geometrical properties of the order cone associated with the Loewner order. To this end a modification of the HSL-colour model and a relativistic addition of matrices is introduced. Some experiments performed with elementary morphological operators on synthetic and natural images give an idea of the capabilities and limitations of the novel approach.

3.2 Control and Edit Higher-Order Tensor Fields for Hex-Meshing

Guoning Chen (University of Houston, US)

Hexahedral meshes have been widely applied in the areas of mechanical engineering, bio-mechanics, and many others. Compared to the easily generated tetrahedral meshes, hex-meshes offer a number of desired characteristics. For example, they are 1) locally structured and thus favor the exploiting of tensor product structure; 2) easy to refine, facilitating the implementation of multi-grid and adaptive computations; 3) having larger tolerance for anisotropy and less numerical stiffness. These characteristics facilitate subsequent scientific computations that are run on these meshes, such as certain physically-based simulations, so that the generated results are of higher accuracy and faster to compute.

Recently introduced techniques rely on either PolyCube map or a 3D cross field, a 4th-order symmetric tensor field, to compute a 3D parameterization of the volume for the generation of the hex-meshes. PolyCube map approach focuses on the structure of the parameterization near surfaces and can be considered, in some sense, a special case of the cross field approach, which provides information of the interior structure of the 3D parameterization as well. However, the structure of the generated hex-meshes, determined by the irregular edges and vertices, with either method is hard to predict and control.

We recently introduced a method to combine the advantages of the Polycube approach and the cross field method to achieve certain level of explicit control of the hex-mesh structure. The structure of the hex-meshes generated by our method is typically very simple, i.e. having fewer hexahedral elements or larger tensor product structure. This facilitates the subsequent data fitting process. However, the generated hex-meshes exhibit large local distortion in certain areas due to the enforcement of simplicity of the structure. We are currently investigating the possible operations that allow us to refine this simple structure by introducing more smaller hexahedral components to reduce the local distortion. On the other hand, we are interested in simplifying the structure of the hex-meshes generated by other methods. Either problem requires the understanding of the valid topological operations of a higher-order tensor field, to which the structure of the hex-mesh can be mapped, so that all-hex configuration of the mesh is preserved and no T-junctions are introduced during the modification. What are those possible valid operations? I would like to discuss this in the seminar.

3.3 Geometrical Diffusion Imaging

Tom Dela Haije (TU Eindhoven, NL)

Joint work of Dela Haije, Tom; Fuster, Andrea; Florack, Luc

By analyzing the behavior of stochastic processes on a Riemannian manifold, in particular Brownian motion, one can deduce the metric structure of the space. This fact was implicitly used by O'Donnell et al. in a 2002 paper, in which diffusion tensor imaging data of the brain was cast into a Riemannian framework. By presuming the existence of an inner product, intuitively defined by the inverse of the diffusion tensor, they could for example visualize the apparent connectivity between different brain regions. Conversely it is possible to derive the stipulated relation between the diffusion tensor and the Riemannian metric tensor from this inner product presumption alone.

In this work we present an attempt to generalize the Riemannian diffusion MRI framework to a Finsler geometry setting, relying only on the existence of a more general norm than the one induced by an inner product. We investigate if and how this allows the diffusion weighted MRI signal to be related to the Finslerian metric structure.

3.4 Visual Embedding: A Model for Visualization

Çağatay Demiralp (Stanford University, US)

Joint work of Demiralp, Çağatay; Heer, Jeffrey
Main reference http://www.cs.stanford.edu/~cagatay/vismodel/vismodel.pdf

In my talk, I'll propose visual embedding as a model for automatically generating and evaluating visualizations. A visual embedding is a function from data points to a space of visual primitives that measurably preserves structures in the data (domain) within the mapped perceptual space (range). I'll demonstrate with examples that visual embedding can serve as both a generative and an evaluative model. I'll briefly discuss techniques for generating visual embedding functions, including probabilistic graphical models for embedding within discrete visual spaces. I'll also describe two complementary approaches–crowdsourcing and visual product spaces–for building visual spaces with associated perceptual distance measures (perceptual kernels). I'll finish my talk by presenting future research directions for further developing the visual embedding model.

3.5 DTI Interpolation in 5 Dimensions

Luc Florack (TU Eindhoven, NL)

Joint work of Florack, Luc; Dela Haije, Tom; Fuster, Andrea
Main reference L. M. J. Florack, A. Fuster, "Riemann-Finsler Geometry for Diffusion Weighted Magnetic Resonance Imaging", in C.-F. Westin, A. Vilanova, B. Burgeth, eds., "Visualization and Processing of Tensors and Higher Order Descriptors for Multi-Valued Data", Springer-Verlag, 2014, to appear.

Diffusion Tensor Imaging (DTI) is a well-known model for the representation of diffusion weighted magnetic resonance images. It is popular by virtue of its simplicity and the fact that it strikes a good balance between signal fit and robustness. However, problematic issues remain. One of these concerns the problem of subvoxel spatial interpolation, especially in highly inhomogeneous regions. As an example, consider two similar white matter fiber bundles in a planar sheet, crossing at right angles. Off-center the (level sets of the) apparent diffusion coefficients (ADCs), which in the DTI model are quadratic forms in the q-space variable, are prolate spheroids that capture the directions of the individual bundles well. However, because the DTI assumption forces ADCs to fit quadratic forms, destructive interference of diffusivity patterns within the crossing region results in oblate spheroids, completely erasing any information on the interfering directionalities. This phenomenon also affects interpolation of DTI data. For certain applications, notably tractography, one would like an interpolated DTI tensor to reflect not only some weighted average of its given grid neighbours, but also to support a priori knowledge about the direction of tracking. For instance, when considering interpolation in the aforementioned example it would make sense to stress the prolate spheroids along one of the two bundles if one happens to be tracking in the direction of that bundle, resulting in an appropriate prolate spheroidal interpolation profile rather than an indeterminate figure. It turns out possible to do this from a single interpolation (not requiring the specification of an a priori preferred direction) involving all grid points in the volumetric neighbourhood of the subvoxel location of interest. However, the interpolated ADC function ceases to be a quadratic form, but constitutes a (much richer) homogeneous function of degree 2 with respect to the q-space variable. The indicatrix (a fiducial level set of this function) is still convex, but no longer ellipsoidal. Any choice of a preferred direction singles out an ellipsoidal, so-called "osculating indicatrix", corresponding to a quadratic form. In other words, one may regard the interpolated ADC as a family of DTI tensors, parametrized by orientation. Orientation thus adds two dimensions to the three dimensional spatial domain, forming a so-called projective sphere bundle.

3.6 Geodesic Interpolation of Fourth-order Tensors

Andrea Fuster (TU Eindhoven, NL)

Joint work of Fuster, Andrea; Schultz, Thomas

Tensor interpolation is valuable for any application requiring computation of tensor values at subvoxel level or in between data points. One of the alternatives to component-wise linear interpolation is the so-called geodesic interpolation proposed by Pennec et al. In this framework, second-order tensors are considered to live in a certain Riemannian manifold, and the geodesic connecting two tensors is used to find the interpolated tensor. We propose to apply this framework to the interpolation of fourth-order tensors, by considering the corresponding six-dimensional matrization. In doing so, we distinguish two cases: fourth-order tensors satisfying major and minor symmetries, e.g. elasticity tensors, and those being totally symmetric such as higher-order diffusion tensors.

3.7 Comparative Visual Analysis of Lagrangian Transport Measures in Ensembles

Christoph Garth (TU Kaiserslautern, DE)

Joint work of Garth, Christoph; Hummel, Mathias; Obermaier, Harald
Main reference M. Hummel, H. Obermaier, C. Garth, K. I. Joy, "Comparative Visual Analysis of Lagrangian Transport in CFD Ensembles," IEEE Trans. Vis. Comput. Graph., 19(12):2743–2752, 2013.
URL http://dx.doi.org/10.1109/TVCG.2013.141

Sets of simulation runs based on parameter and model variation, so-called ensembles, are increasingly used to model physical behaviors whose parameter space is too large or complex to be explored automatically. Visualization plays a key role in conveying important properties in ensembles, such as the degree to which members of the ensemble agree or disagree in their output. For ensembles of time-varying vector fields, there are numerous challenges for providing an expressive comparative visualization, among which is the requirement to relate the effect of individual flow divergence to joint transport characteristics of the ensemble. Yet, techniques developed for scalar ensembles are of little use in this context, as the notion of transport induced by a vector field cannot be modeled using such tools. We report on recent work towards developing a framework for the comparison of flow fields in an ensemble, and speculate on applications of our framework to tensor fields.

3.8 Moment Invariants for Pattern Recognition

Hans Hagen (TU Kaiserslautern, DE) and Max Langbein (TU Kaiserslautern, DE)

Joint work of Hagen, Hans; Langbein, Max

Higher-order moment tensors are a very generic description of the local behavior in point-clouds, scalar, vector, and tensor fields. Having a method at hand to compute the values of a complete and independent set of invariants from then from them in a efficient and robust manner, this can be used to recognize objects and features in fields and in surfaces described by point-clouds. In this talk, the computation of a specific type of invariants and their use to recognize features in point-clouds will be described.

3.9 Heat Kernel Signature for Tensor Fields

Ingrid Hotz (German Aerospace Center – Braunschweig, DE)

Joint work of Hotz, Ingrid; Zobel, Valentin; Reininghaus, Jan

We propose a method for visualizing two-dimensional symmetric tensor fields using the Heat Kernel Signature (HKS). The HKS is derived from the heat kernel and was originally introduced as an isometry invariant shape signature. The time parameter of the heat kernel allows a multi-scale analysis in a natural way. By considering a positive definite tensor field as a Riemannian metric the definition of the HKS can be applied directly. To investigate how this measure can be used to visualize more general tensor fields we apply mappings to obtain positive definite tensor fields. The resulting scalar quantity is used for the visualization of tensor fields. For short times it is closely related to Gaussian curvature, i.e. it is quite different to usual tensor invariants like the trace or the determinant.

3.10 Learning Optimal Q-space Sampling Metrics

Hans Knutsson (Linköping University Hospital, SE)

We present a novel approach to determine a local q-space metric that is optimal from an information theoretic perspective with respect to the expected signal statistics. The signal statistic is obtained from the expected distribution of the diffusion propagators present. The obtained metric can then serve as a guide for the generation of specific q-space sample distributions. It should be noted that the approach differs significantly from the classical estimation theory approach, e.g. one based on Cramer-Rao bounds. The latter requires a pre-defined mathematical representation, the estimator. Our suggestion aims at obtaining the maximum amount of information without enforcing a particular feature representation.

To obtain the statistics of the q-space signals we generate a large number of q-space response examples. Using these examples correlation estimates between any two q-space locations, as well as correlations between different instances of the same location, can be estimated. From these correlations the added information from measuring in a second q-space location, given a first measurement in any other location, can be found.

3.11 Engineering Tensor Visualization: To ML or not ML?

Georgeta Elisabeta Marai (University of Pittsburgh, US)

Joint work of Marai, Georgeta Elisabeta; Givi, Peyman; Yilmaz, Levent; Mehdi, Nik; Maries, Adrian

Computational tensor fields are very large and spatially dense. We attempt to identify effective visual descriptors for volume rendering the combustion tensor data. Does Machine Learning (ML) for Visualization capture features of interest in such data sets? We evaluate several visual descriptors, including the result of a machine learning classification technique, on several computational-combustion data sets and report on our findings.

3.12 Finding Ring-like Patterns in Local Orientation Distributions

Rodrigo Moreno (Linköping University Hospital, SE)

Vesselness filters aim at enhancing tubular structures in medical images. The most popular vesselness filters are based on Eigen analyses of the Hessian matrix. However, Hessian-based methods have well-known limitations, most of them related to the use of second-order derivatives. In this talk, I propose an alternative strategy in which ring-like patterns are sought in local orientation distribution of gradients. The method takes advantage of the symmetry properties that these ring-like patterns show in the spherical harmonics domain. From such an analysis, a vesselness measurement is proposed.

In order to discourage the enhancement of dark vessels, gradients not pointing towards the center are filtered out from every local neighborhood in a first step. Afterwards, an orientation distribution is generated from the remaining gradients which are weighted with a Gaussian filter. Next, the power spectrum in spherical harmonics is computed for both the original and a half-zeroed orientation distribution. From both power spectra, the even, odd and DC components are extracted. Finally, the even and DC ratios of both distributions plus the strength of the original distribution are combined into a single vesselness measurement. Preliminary results show that the proposed filter performs better compared to traditional approaches in both synthetic and computed tomography angiography data.

3.13 White Matter Asymmetry Methods using Diffusion MRI

Lauren O'Donnell (Harvard Medical School – Boston, US)

Brain asymmetries provide mysterious clues about the brain's functional organization. For example, known left-greater-than-right asymmetries relate to the localization of language function to the left hemisphere in most right-handed subjects. But interestingly, increased symmetry of the arcuate fasciculus (language-related) fiber tract correlates with improved verbal recall performance. Much remains to be learned about how morphological symmetries may underlie major functional differences across the hemispheres.

The development of new methods to measure white matter (WM) asymmetry using diffusion tensor MRI (DTI) may provide biomarkers for presurgical localization of language function and improve our understanding of neural structure-function relationships in health and disease. The question of how best to measure WM asymmetry is open. We will review existing methods for the study of WM asymmetry and present results from a hypothesis-free method for measurement of asymmetry in the entire WM.

3.14 Mean Apparent Propagator (MAP) MRI: A Novel Representation of Three-Dimensional Diffusion MRI Data

Evren Özarslan (Bogaziçi University – Istanbul, TR)

Joint work of Özarslan, Evren; Koay, Cheng Guan; Shepherd, Timothy M.; Komlosh, Michal E.; Irfanoglu, M. Okan; Pierpaoli, Carlo; Basser, Peter J.
Main reference E. Özarslan, C. G. Koay, T. M. Shepherd, M. E. Komlosh, M. Okan Irfanoğlu, C. Pierpaoli, P. J. Basser, "Mean Apparent Propagator (MAP) MRI: a novel diffusion imaging method for mapping tissue microstructure," Neuroimage, 78:16–32, September 2013.
URL http://dx.doi.org/10.1016/j.neuroimage.2013.04.016

Diffusion-weighted Magnetic Resonance (MR) signals can be transformed into profiles of diffusive displacements, which contain information about underlying tissue microstructure and cytoarchitecture. We previously proposed [1] an efficient representation of the MR signal decay via Hermite functions leading to accurate estimates in the high- as well as low-frequency regimes of the displacement profiles. MAP-MRI [2] is a new framework that combines three such representations with possibly different scale parameters assigned to each of the three principal orientations of diffusion. The lowest order term on the resulting series contains a diffusion tensor that characterizes the Gaussian displacement distribution, equivalent to that assumed by diffusion tensor MRI (DTI), while inclusion of higher order terms enables the reconstruction of the true apparent propagator. Since the propagator is represented as a vector in an abstract space, it is meaningful to measure the (dis)similarity of two propagators via an angular metric. Such a measure was used to introduce several scalar indices leading to interesting contrasts in the brain. MAP-MRI's overall mathematical structure resembles tensorial representations albeit with different transformation properties.

References

1 Özarslan, E., Koay, C. G., Basser, P. J., 2008. Simple harmonic oscillator based estimation and reconstruction for one-dimensional q-space MR. In: Proc Intl Soc Mag Reson Med. Vol. 16. p. 35.
2 Özarslan, E., Koay, C. G., Shepherd, T. M., Komlosh, M. E., İrfanoğlu, M. O., Pierpaoli, C., Basser, P. J., 2013. Mean apparent propagator (MAP) MRI: a novel diffusion imaging method for mapping tissue microstructure. NeuroImage 78, 16–32.

3.15 Multiscale Feature Preserving Volume Visualization

Renato Pajarola (Universität Zürich, CH)

Joint work of Pajarola, Renato; Suter, Susanne K.
Main reference S. K. Suter, M. Makhinya, R. Pajarola, "TAMRESH: Tensor approximation multiresolution hierarchy for interactive volume visualization," Computer Graphics Forum, 32(3pt2):151–160, 2013.
URL http://dx.doi.org/10.1111/cgf.12102

In this talk we will review a novel and recently proposed method for higher-order decomposition of large scale multi-dimensional visual data into multi-linear bases and corresponding coefficients, suitable for interactive visualization applications. This tensor-approximation based volume representation features compact data storage, it supports efficient spatially selective random access at variable resolution, and it allows for multi-scale feature preserving reconstruction; all critical and desired properties in an interactive scientific visualization environment. We will also focus on and discuss the multi-scale feature expressiveness of such data decomposition and reconstruction approaches, as well as on further data processing that can be supported efficiently in the decomposition domain.

3.16 Diffusion Tensors from Double-PFG MRI Experiments

Ofer Pasternak (Harvard Medical School – Boston, US)

Double-pulsed field gradient (double PFG) is a generalization of the single PFG acquisition methods that is conventionally used in diffusion MRI. Instead of applying a single pair of sensitizing gradients, the double PFG acquisition applies two pairs of sensitizing gradients (separated by a mixing time), and as a result the attenuation is affected by the combined effect of molecule displacement during the two pairs. The approach was recently implemented on clinical scanners, allowing in-vivo human scans. Different applications have demonstrated that varying the angle between the two pairs result with signal modulation that provides information about anisotropies that cannot be measured with single PFG. Double PFG was also utilized to measure exchange between compartments. In this context of exchange measurement, it is common to refer to the first gradient block as a filtering block, which is designed to attenuate fast diffusing water molecules, such as those found in the extracellular space. Here, we propose to use the terminology of filtering blocks, combined with a specialized gradient acquisition scheme in order to provide a simple model, which relates a special case of the double PFG signal to diffusion tensors. By using a tensor model we are able to make an intuitive connection between the single and double PFG methods, which also allows application of existing DTI analysis methods and tools.

3.17 Frames for Tensor Field Morphology

Jos B. T. M. Roerdink (University of Groningen, NL)

Joint work of Van de Gronde, Jasper J.; Roerdink, Jos B.T.M.
Main reference J. J. van de Gronde, Jos B. T. M. Roerdink, "Frames for Tensor Field Morphology," in Proc. of the 1st Int'l Conf. on Geometric Science of Information (GSI'13), LNCS, Vol. 8085, pp. 527–534, Springer, 2013; the author provides a webpage with related sourcecode.
URL http://dx.doi.org/10.1007/978-3-642-40020-9_58
URL http://bit.ly/15MoLEI

Initiated in the 1960s, mathematical morphology was developed to describe image operators for enhancement, segmentation, and extraction of shape information from digital images. In contrast to traditional linear image processing, the morphological image operators focus on the geometrical content of images and are nonlinear. Their mathematical description has been extensively developed within the framework of partial orders and complete lattice theory, and many efficient algorithms are available for binary and grey scale images. Also, the case of vector-valued data, such as color or hyper-spectral images, has been addressed. Our current work focuses on the development of (hyper-) connected, adaptive and multi-scale morphological filters for matrix- and tensor-valued images. A major hurdle is the fact that there is no obvious partial order on tensors.

From the theoretical point of view, an important aspect in the design of morphological operators is their invariance under translation, rotation or scale changes, or, more generally, under an arbitrary group of transformations. A recent approach to group invariance (and particularly rotation invariance) for tensor fields is presented, based on the concept of frames. Open problems will be discussed.

References

1. Jasper J. van de Gronde and Jos B. T. M. Roerdink. *Group-Invariant Frames for Colour Morphology*. Proc. 11th International Symposium on Mathematical Morphology (ISMM 2013), May 27-29, Uppsala, Sweden, C. L. Luengo Hendriks, G. Borgefors and R. Strand (eds.), LNCS 7883, 267–278, 2013.
2. Jasper J. van de Gronde and Jos B. T. M. Roerdink. *Frames for Tensor Field Morphology*. Proc. Geometric Science of Information, F. Nielsen and F. Barbaresco (eds.), LNCS 8085, 527–534, 2013.
3. Jasper J. van de Gronde and Jos B. T. M. Roerdink. *Group-Invariant Colour Morphology Based on Frames*. IEEE Transactions on Image Processing, 23 (3), 1276–1288, 2014.

3.18 Tensor Lines in Engineering – Success and Open Questions

Gerik Scheuermann (Universität Leipzig, DE)

Joint work of Scheuermann, Gerik; Zobel, Valentin; Stommel, Markus; Schöneich, Marc; Burgeth, Bernhard; Kratz, Andrea; Hotz, Ingrid

After the previous Dagstuhl meeting on Tensor Processing and Visualization, a team of mathematicians, visualization researchers, and engineers started an intense cooperation. This became a real success story: Tensor lines can sometimes lead to substantially better component designs, especially for rib design. However, in other cases, we were not able to repeat this success. In the talk, we review the success and failure cases and suggest directions of further research.

3.19 Tensor Visualization – A Tool for Engineers in the Virtual Product Development Process

Marc Schöneich, Markus Stommel (Universität des Saarlandes, DE)

Joint work of Kratz, Andrea; Schöneich, Marc; Zobel, Valentin; Burgeth, Bernhard; Scheuermann, Gerik; Hotz, Ingrid; Stommel, Markus
Main reference A. Kratz, M. Schöneich, V. Zobel, B. Burgeth, "Tensor Visualization Driven Mechanical Component Design," in Proc. of the 2014 IEEE Pacific Visualization Symp. (PacificVis'14), pp. 145–152, IEEE, 2014.
URL http://dx.doi.org/10.1109/PacificVis.2014.51

This contribution starts with a short introduction to nowadays development process of technical parts. Important computer aided tools are described which are used by the engineer in the context of virtual product development. Based on typical time schedules of product development processes the need for efficient visualization tools for the engineer is derived. This not only aimed at producing powerful pictures by visualization techniques but also in filtering the multidimensional data towards significant information and using as much as possible of the information in i.e. tensorial technical information.

The significance of tensor visualization in designing technical parts is presented in the second part as a major result of a close collaboration between mechanical engineers and visualization researchers to base the part topology optimization on visualisation techniques using specific tensorial information. The investigated tensor lines (lines tangential to the principal stresses) are related to the major load paths from the operating loads to the fixation points of a technical part. Hence, tensor lines can be considered as a central component in the structure design process. The guidance of the design of rip structures in injection moulded plastic parts by selected tensor lines will result in an optimized rip structure which leads to stiffer parts with identical material use. FE simulations as well as experimental tests validate the optimization potential of tensor line visualization for the design of ribbed plastic components.

At the end of the contribution still open questions and limitations of using tensorial data and visualization techniques will be addressed.

3.20 Kernel Distribution Embeddings: Applications to Diffusion MRI

Thomas Schultz (Universität Bonn, DE)

Joint work of Schultz, Thomas; Schlaffke, Lara; Schölkopf, Bernhard; Schmidt-Wilcke, Tobias
Main reference T. Schultz, L. Schlaffke, B. Schölkopf, T. Schmidt-Wilcke, "HiFiVE: A Hilbert Space Embedding of Fiber Variability Estimates for Uncertainty Modeling and Visualization," Computer Graphics Forum, 32(3pt1):121–130, 2013.
URL http://dx.doi.org/10.1111/cgf.12099

Recently, the popular and successful idea of using kernels to map individual points to feature spaces has been extended to produce feature space representations of probability distributions. This talk will provide a gentle introduction to this topic and explain how it naturally leads to a higher-order descriptor of the uncertainty in fiber directions estimated from diffusion MRI. I will show examples in which this novel descriptor is successfully applied for uncertainty visualization and for improved segmentation of gray matter structures such as the thalamus.

3.21 Mathematical Review of NMR Signal with Restricted Diffusion

Nir Sochen (Tel Aviv University, IL)

Joint work of Bar, Leah; Sochen, Nir; Morozov, Daria; Cohen, Yoram

We review the solution to the Bloch-Torrey equations via the Multiple Correlation Function (MCF) frame work. The single and double pulse field gradients are analysed via this framework. We show how one can use a direct extension of the MCF. The direct approach coincides with the indirect approach of Özerslan and Basser for certain geometries and extends it in the spherical case. An inverse process is applied to recover the geometric data. Experiments on phantoms with mixture of geometries are with good fit to the theory.

3.22 Diffusion Measurement Tensors

Carl-Fredrik Westin (Harvard Medical School – Boston, US)

Joint work of Westin, Carl-Fredrik; Knutsson, Hans; Nilsson, Markus

Diffusion MRI and NMR is one of the most dynamic and cutting-edge areas of imaging science and NMR physics, but the vast majority of applications focus on the simplest form of the basic experiment, the Stejskal-Tanner pulse sequences, which we refer to here as single pulsed field gradient (sPFG) experiment. sPFG typically is used to measure the mean diffusion (apparent diffusion coefficient, ADC) and diffusion anisotropy (Fractional Anisotropy, FA). Although current popular diffusion measures are very sensitive to changes in the cellular architecture, they are not very specific regarding the type of change. These measures provide crude markers of cellular disruption, since cell damage tends to break down semi-permeable cell walls increasing water mobility and thus the observed diffusivity.

We are at the cusp of a completely new generation of diffusion MRI technologies, which has the potential to transform what is possible with the technique via non-conventional underlying pulse sequences. The traditional sPFG sequence generates a diffusion measurement tensor of rank-1. We will review the family of new emerging technologies, and discuss how these techniques will allow for direct diffusion measurements of higher than rank-1.

3.23 Tensor Field Analysis: Some Open Problems

Eugene Zhang (Oregon State University, US)

Tensor fields have a wide range of applications in science, engineering, medicine, and image processing. There have been much work by the image processing, medical imaging, and scientific visualization communities, leading to vast amount of knowledge of 2D and 3D tensor fields.

In this talk, I would like to discuss a number of problems which I believe can provide critical insights on furthering our understanding of 3D tensor fields.

4 List of Previous Meetings in this Seminar Series

- The 2004 Dagstuhl Perspective Workshop "Visualization and Processing of Tensor Fields" (Perspectives Workshop 04172, April 2004, Organizers: Hans Hagen and Joachim Weickert) was the first international forum where leading experts on visualization and processing of tensor fields had the opportunity to meet, many for the first time. This workshop identified several key issues and triggered fruitful collaborations that have also led to the first book in this area. Springer book published in 2006: ISBN 978-3-540-25032-6.
- The 2007 Dagstuhl Seminar "Visualization and Processing of Tensor Fields" (Seminar 07022, January 2007, Organizers: David Laidlaw and Joachim Weickert) was equally successful and the progress reported in a second book published with Springer published in 2009: ISBN 978-3-540-88377-7.
- The 2009 Dagstuhl Seminar "New Developments in the Visualization and Processing of Tensor Fields" (Seminar 09302, July 2009, Organizers: Bernhard Burgeth and David Laidlaw) saw a shift in focus, and in addition to diffusion imaging, paid attention to engineering applications of tensors in fluid mechanics, material science, and elastography. Springer has also published a third book in this series: ISBN 978-3-642-27342-1.
- The 2011 Dagstuhl Seminar "Visualization and Processing of Tensors and Higher Order Descriptors for Multi-Valued Data" (Seminar 11501, December 2011, Organizers: Bernhard Burgeth, Anna Vilanova and Carl-Frederik Westin) focussed on modern and emerging methods for analysis and visualization of tensor and higher-order descriptors from medical imaging and engineering applications. The subject of the seminar series saw a shift where higher-order descriptors that went beyond tensors were explicitly addressed. The meeting resulted in a book that is at the moment of writing in the editorial stage, and is expected to be published around May 25 of this year.

5 Additional Outcomes of Previous Meeting

After meeting Gary Zhang at the Dagstuhl Seminar in 2011, Lauren O'Donnell and Thomas Schultz got involved in the organization of the following workshops:

- MICCAI 2012 Workshop on Computational Diffusion MRI, Nice, France.
- MICCAI 2013 Workshop on Computational Diffusion MRI, Nagoya, Japan.
- MICCAI 2014 Workshop on Computational Diffusion MRI, Boston, MA, USA.

The 2013 workshop resulted in the publication of the book Computational Diffusion MRI and Brain Connectivity (ISBN 978-3-319-02475-2) edited among others by Thomas Schultz and Lauren O'Donnell, and with contributions by a number of the attendees of the 2011 Dagstuhl Seminar.

Finally the seminar also resulted in a successful "Landesforschungsförderprogramm (LFFP) des Saarlandes" grant proposal.

6 Schedule

	Monday	Tuesday	Wednesday	Thursday	Friday
09:00	Introduction	Nir Sochen (20) Ofer Paternak (20)	Tom Dela Haije (20) Cagatay Demiralp (30)	Markus Stommel + Marc Schöneich (40)	
09:30	Breakout sessions				Book Breakout summary
10:00	Thomas Schultz (20)				
10:30	Coffee Break				
11:00	Luc Florack (20)	Hans Knutsson (20)	Andrea Fuster (15)	Gerik Scheuermann (15)	Breackout summary
11:30	Ingrid Hotz (20)	C.-F. Westin (20)	Eugene Zhang (30)	G. Elisabeta Marai (15)	Goodbye
12:00	Lunch (12:15)				
12:30					
13:00					
13:30	Renato Pajarola(20) Guoning Chen (15) Lauren O'Donnell (15)	Evren Ozerslan (20) Jos Roerdink (20) Bernhard Burgeth(15)	Social Event	Max Langbein (15) Christoph Garth (15) Rodrigo Moreno (15)	
14:00					
14:30					
15:00					
15:30	Coffee Break			Coffee Break	
16:00	Breakout sessions	Breakout sessions		Breakout sessions	
16:30					
17:00					
17:30					
18:00	dinner				

Participants

- Bernhard Burgeth
Universität des Saarlandes, DE
- Guoning Chen
University of Houston, US
- Tom Dela Haije
TU Eindhoven, NL
- Çağatay Demiralp
Stanford University, US
- Luc Florack
TU Eindhoven, NL
- Andrea Fuster
TU Eindhoven, NL
- Christoph Garth
TU Kaiserslautern, DE
- Hans Hagen
TU Kaiserslautern, DE
- Ingrid Hotz
German Aerospace Center – Braunschweig, DE
- Hans Knutsson
Linköping Univ. Hospital, SE
- Max Langbein
TU Kaiserslautern, DE
- Georgeta Elisabeta Marai
University of Pittsburgh, US
- Rodrigo Moreno
Linköping Univ. Hospital, SE
- Lauren O'Donnell
Harvard Medical School – Boston, US
- Evren Özarslan
Bogaziçi Univ. – Istanbul, TR
- Renato Pajarola
Universität Zürich, CH
- Ofer Pasternak
Harvard Medical School – Boston, US
- Jos B.T.M. Roerdink
University of Groningen, NL
- Gerik Scheuermann
Universität Leipzig, DE
- Marc Schöneich
Universität des Saarlandes, DE
- Thomas Schultz
Universität Bonn, DE
- Nir Sochen
Tel Aviv University, IL
- Markus Stommel
Universität des Saarlandes, DE
- Anna Vilanova
TU Delft, NL
- Carl-Fredrik Westin
Harvard Medical School – Boston, US
- Eugene Zhang
Oregon State University, US